

Global Air Quality and Health Co-benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls

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BACKGROUND: Tropospheric ozone and black carbon (BC), a component of fine particulate matter ($PM \leq 2.5 \mu m$ in aerodynamic diameter; $PM_{2.5}$), are associated with premature mortality and they disrupt global and regional climate.

OBJECTIVES: We examined the air quality and health benefits of 14 specific emission control measures targeting BC and methane, an ozone precursor, that were selected because of their potential to reduce the rate of climate change over the next 20–40 years.

METHODS: We simulated the impacts of mitigation measures on outdoor concentrations of $PM_{2.5}$ and ozone using two composition-climate models, and calculated associated changes in premature $PM_{2.5}$ - and ozone-related deaths using epidemiologically derived concentration–response functions.

RESULTS: We estimated that, for $PM_{2.5}$ and ozone, respectively, fully implementing these measures could reduce global population-weighted average surface concentrations by 23–34% and 7–17% and avoid 0.6–4.4 and 0.04–0.52 million annual premature deaths globally in 2030. More than 80% of the health benefits are estimated to occur in Asia. We estimated that BC mitigation measures would achieve approximately 98% of the deaths that would be avoided if all BC and methane mitigation measures were implemented, due to reduced BC and associated reductions of non-methane ozone precursor and organic carbon emissions as well as stronger mortality relationships for $PM_{2.5}$ relative to ozone. Although subject to large uncertainty, these estimates and conclusions are not strongly dependent on assumptions for the concentration–response function.

CONCLUSIONS: In addition to climate benefits, our findings indicate that the methane and BC emission control measures would have substantial co-benefits for air quality and public health worldwide, potentially reversing trends of increasing air pollution concentrations and mortality in Africa and South, West, and Central Asia. These projected benefits are independent of carbon dioxide mitigation measures. Benefits of BC measures are underestimated because we did not account for benefits from reduced indoor exposures and because outdoor exposure estimates were limited by model spatial resolution.

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Tropospheric ozone and black carbon (BC), a component of fine particulate matter ($PM \leq 2.5 \mu m$ in aerodynamic diameter; $PM_{2.5}$), have been associated with deleterious effects on human health (e.g., Jerrett et al. 2009; Laden et al. 2006; Pope et al. 2002), agriculture (e.g., Ashmore 2005), and climate (e.g., Ramanathan and Carmichael 2008). Methane, a relatively short-lived greenhouse gas (residence time 8–10 years), is an ozone precursor that affects background ozone concentrations. Controlling methane emissions may be a promising means of simultaneously mitigating climate change and reducing global ozone concentrations, compared with controlling shorter-lived ozone precursors [nitrogen oxides (NO_x), carbon monoxide (CO), and non-methane volatile

organic compounds (NMVOCs)] (West et al. 2006, 2007). The latter may have larger and more immediate air quality and health benefits near the areas with emission reductions but smaller benefits (CO , NMVOC) or net disbenefits (NO_x) for climate. Major anthropogenic sources of methane include fossil fuel production and distribution, landfills, livestock, rice cultivation, and wastewater treatment. BC is a product of incomplete combustion from sources such as biomass burning, transportation (mainly diesel vehicles), residential combustion, and industry, and is coemitted with other pollutants, including NO_x , NMVOCs, CO , sulfur dioxide (SO_2), and organic carbon. Climate benefits of reducing BC may be partially offset by associated reductions of

coemitted pollutants that may have a net cooling effect on climate (and a net warming effect when reduced), either directly (organic carbon) or after chemical transformation in the atmosphere (organic carbon, SO_2 , and NO_x). However, all emission reductions leading to reduced ozone and $PM_{2.5}$ concentrations would be expected to have health benefits.

Mitigating ozone and BC may benefit climate and health simultaneously (e.g., Jacobson 2002; Smith et al. 2009; West et al. 2006); because methane and BC are short-lived relative to the long-lived greenhouse gases [e.g., carbon dioxide (CO_2)], mitigation would reduce the rate of climate change in the near-term (Jackson 2009; Ramanathan and Carmichael 2008). Although a recent series of studies has examined the ancillary health benefits of greenhouse gas mitigation (Haines et al. 2009), the health benefits of mitigating ozone and BC as climate forcers have been studied less extensively. Studies examining the health impacts of all fossil fuel and biofuel emissions (Jacobson 2010), percentage reductions in ozone precursors (West et al. 2006) and BC (Anenberg et al. 2011), and adoption of European vehicle emission standards in the

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developing world (Shindell et al. 2011) suggest that controlling methane and BC emissions may substantially benefit global public health, particularly in Asia where large populations are exposed to high PM_{2.5} and ozone concentrations (Ramanathan et al. 2008).

The United Nations Environment Programme (UNEP) and the World Meteorological Organization (WMO) therefore initiated an integrated assessment of the potential climate, health, agricultural, and economic benefits that would be achieved by further implementing methane and BC mitigation measures already employed in various parts of the world (UNEP 2011). In the present study, we used emissions scenarios developed for the UNEP/WMO assessment to examine the potential air quality and health benefits of methane and BC mitigation measures in more detail.

Methods

Emission scenarios and modeling. We used five emissions scenarios developed for the UNEP/WMO assessment to examine methane and BC mitigation impacts on air quality and health globally and in five world regions [see Supplemental Material, Figure 1 (<http://dx.doi.org/10.1289/ehp.1104301>)]. These scenarios include a present-day (2005) reference case, a 2030 reference scenario that incorporates International Energy Agency energy projections (International Energy Agency 2009) and all presently agreed upon (but no additional) policies affecting emissions (see Supplemental Material, Table 2 and Figure 2), and three different policy scenarios in which varying degrees of additional emission controls are implemented by 2030. To isolate the impacts of anthropogenic emission changes, all scenarios

assume identical meteorology and natural emissions [including open biomass burning (i.e., wildfires); year 2000]. The emission scenarios and their projected effects on climate are detailed by Shindell et al. (2012) and are summarized in Supplemental Material, pp. 4–9.

We selected the three policy scenarios based on an evaluation of the potential climate impacts of approximately 2,000 mitigation measures defined in the International Institute for Applied Systems Analysis (IIASA) Greenhouse Gas and Air Pollution Interactions and Synergies (GAINS) model (Amann et al. 2011). Climate impacts of each measure were classified according to CO₂ equivalence, which was calculated based on global warming potential (GWP) over a 100-year time horizon for predicted methane, CO, SO₂, NO_x, NMVOCs, BC, organic carbon, and CO₂ emission changes following implementation of the control measure (Shindell et al. 2012). Based on this evaluation, we identified 14 individual methane and BC control measures that would achieve approximately 90% of the climate benefits feasible for all of the evaluated measures combined (according to the CO₂ equivalence metric). The 14 measures were grouped into three increasingly stringent policy scenarios for 2030 [Table 1; see also Supplemental Material, pp. 4–8 (<http://dx.doi.org/10.1289/ehp.1104301>)]. The first scenario includes seven technological measures for controlling methane emissions. The second adds four technological measures (BC group 1) for reducing emissions of incomplete combustion, including implementation of Euro 6 and Euro VI equivalent vehicle emission standards (requiring installation of diesel particulate filters) (European Union 2010, 2011) and improving traditional biomass cook

stoves in developing countries. We assumed that emission factors for cook stoves would decline in all regions to levels consistent with emissions from rocket stoves, resulting in a 25% decrease in BC and 80–90% decreases in other species, including organic matter, CO, NMVOC, methane, and direct PM_{2.5}, relative to emissions from traditional stoves (MacCarty et al. 2008). Realistically, emission reductions from cookstoves could be lower depending on stove adoption and use; however, other stove technologies may also be more effective at lowering emissions. Finally, the third and most stringent policy scenario adds three regulatory measures (BC group 2) to eliminate high-emitting vehicles, biomass cook stoves (in developing countries), and agricultural waste burning.

We simulated ozone and PM_{2.5} concentrations using two global composition-climate models, the NASA Goddard Institute for Space Studies (GISS) model for Physical Understanding of Composition-Climate Interactions and Impacts (GISS-PUCCINI; Shindell et al. 2006), and the ECHAM-HAMMOZ model (Pozzoli et al. 2008), referred to here as GISS and ECHAM. We assumed that mitigation measures would be fully implemented and their impacts on concentrations fully realized by 2030. Methane concentrations (accounting for chemical and biological loss processes) were averaged over years 15–19 of each simulation to realize the steady-state effects of methane reductions, although additional minor impacts may occur beyond this period. GISS has a horizontal resolution of 2° latitude × 2.5° longitude with 40 vertical layers from the surface to 0.1 hPa. ECHAM has a horizontal resolution of 2.8° × 2.8° and 31 vertical layers up to 10 hPa. Both models simulate BC, organic carbon, SO₄, sea salt, and dust. GISS also includes nitrate (NO₃). We multiplied simulated organic carbon concentrations by 1.4 to estimate total organic matter concentrations (Cooke et al. 1999). Using a different conversion factor would affect organic matter concentrations proportionally. Because these coarse model resolutions cannot capture fine concentration gradients, particularly for primary PM_{2.5} species (BC and organic carbon) around urban areas, we allocated BC and organic carbon to 0.5° × 0.5° resolution according to population density, following Shindell et al. (2011; see their Supplemental Information). All other species, including ozone, SO₄, and NO₃, were simply regridded to 0.5° × 0.5° resolution, because secondary pollutants are generally more spatially homogeneous. For the main results, we excluded dust and sea salt (which are assumed to be natural) and use the health impact function described below. We also examined the sensitivity of mortality results to inclusion of dust and sea salt and to

Table 1. Description of the 14 methane and BC mitigation measures included in the three increasingly stringent policy scenarios for 2030.

Scenario	Mitigation measure
Methane measures: technical measures for methane emissions	Extended pre-mine degasification and recovery and oxidation of methane from ventilation air from coal mines
	Extended recovery and use—rather than venting—of associated gas and improved control of unintended fugitive emissions from the production of oil and natural gas
	Reduced gas leakage from long-distance transmission pipelines
	Separation and treatment of biodegradable municipal waste through recycling, composting, and anaerobic digestion as well as landfill gas collection with combustion/utilization
	Upgrading primary wastewater treatment to secondary/tertiary treatment with gas recovery and overflow control
	Control of methane emissions from livestock, mainly through farm-scale anaerobic digestion of manure from cattle and pigs
	Intermittent aeration of continuously flooded rice paddies
BC group 1: technical measures for reducing emissions of incomplete combustion	Diesel particle filters as part of a Euro VI package for road and off-road diesel vehicles
	Introduction of clean-burning stoves for cooking and heating in developing countries
	Replacing traditional brick kilns with vertical shaft kilns and Hoffman kilns
	Replacing traditional coke ovens with modern recovery ovens, including the improvement of end-of-pipe abatement measures in developing countries
BC group 2: nontechnical measures to eliminate the most polluting activities	Elimination of high-emitting vehicles in road and off-road transport (excluding shipping)
	Ban of open field burning of agricultural waste
	Substitution of clean-burning cook stoves using modern fuels for traditional biomass cook stoves in developing countries

different magnitudes and shapes of the health impact function.

Health impact assessment. We used epidemiologically derived health impact functions to estimate changes in premature $PM_{2.5}$ - and ozone-related mortality between the 2030 reference scenario and 2005, and between the 2030 reference scenario and the three policy scenarios individually, using 2030 population projections for all scenario comparisons to isolate the impacts of simulated concentration changes. We assumed log-linear relationships between $PM_{2.5}$ or ozone concentrations and relative risks (RR), following Anenberg et al. (2010), and calculated the fraction of baseline deaths attributable to a given change in concentration (attributable fraction; AF) as

$$AF = (RR - 1)/RR = 1 - \exp^{-\beta\Delta X}, \quad [1]$$

where β is the concentration–response factor (CRF, the estimated slope of the log-linear relation between $PM_{2.5}$ or ozone concentration and mortality) and ΔX is the change in pollutant concentration. We multiplied AF by the baseline mortality rate (y_0) and population size (Pop) to estimate the change in premature

deaths ($\Delta Mort$) that would result from a given change in concentration (ΔX):

$$\Delta Mort = y_0 \times Pop \times (1 - \exp^{-\beta\Delta X}). \quad [2]$$

Because disease survival times vary among populations, we estimated the change in years of life lost (ΔYLL) due to a change in premature deaths using the baseline YLL (YLL_0) per death:

$$\Delta YLL = \Delta Mort \times YLL_0/y_0. \quad [3]$$

We applied Equations 2 and 3 in each $0.5^\circ \times 0.5^\circ$ grid cell using corresponding population sizes, baseline mortality and YLL rates, and the simulated changes in $PM_{2.5}$ and ozone concentrations.

We calculated CRFs for $PM_{2.5}$ based on long-term RR estimates starting from the American Cancer Society (ACS) cohort study (Pope et al. 2002). Specifically, for a $10\text{-}\mu\text{g}/\text{m}^3$ increase in annual average $PM_{2.5}$, RRs for all-cause, cardiopulmonary disease, and lung cancer mortality were 1.06 [95% confidence interval (CI): 1.02, 1.11], 1.09 (95% CI: 1.03, 1.16), and 1.14 (95% CI: 1.04, 1.23), respectively, when averaged based on data

for 1979–1983 and 1999–2000. Although the ACS cohort was large compared with other $PM_{2.5}$ cohort studies [e.g., the Harvard Six Cities Study (Laden et al. 2006)], results may underestimate the $PM_{2.5}$ –mortality relationship because well-educated affluent populations are overrepresented in the cohort and because exposure was measured with greater error than in other studies. A 2008 expert elicitation (including ACS authors) produced a mean all-cause mortality CRF estimate [approximately 1.1% mortality increase per $1\text{-}\mu\text{g}/\text{m}^3$ increase in $PM_{2.5}$ (Roman et al. 2008)] that was between the CRFs calculated from the ACS ($\sim 0.6\%$) and Harvard Six Cities Study ($\sim 1.6\%$) RR estimates. The expert elicitation (Roman et al. 2008), however, did not estimate cause-specific RRs, which may be more applicable globally than all-cause mortality. We therefore multiplied the cause-specific CRFs calculated from the Pope et al. (2002) RR estimates by 1.8, the factor difference between the all-cause CRFs from the expert elicitation mean and Pope et al. (2002). A newer ACS reanalysis reported 40% higher cardiopulmonary effect estimates with tighter confidence intervals for all RR estimates (Krewski et al. 2009), but

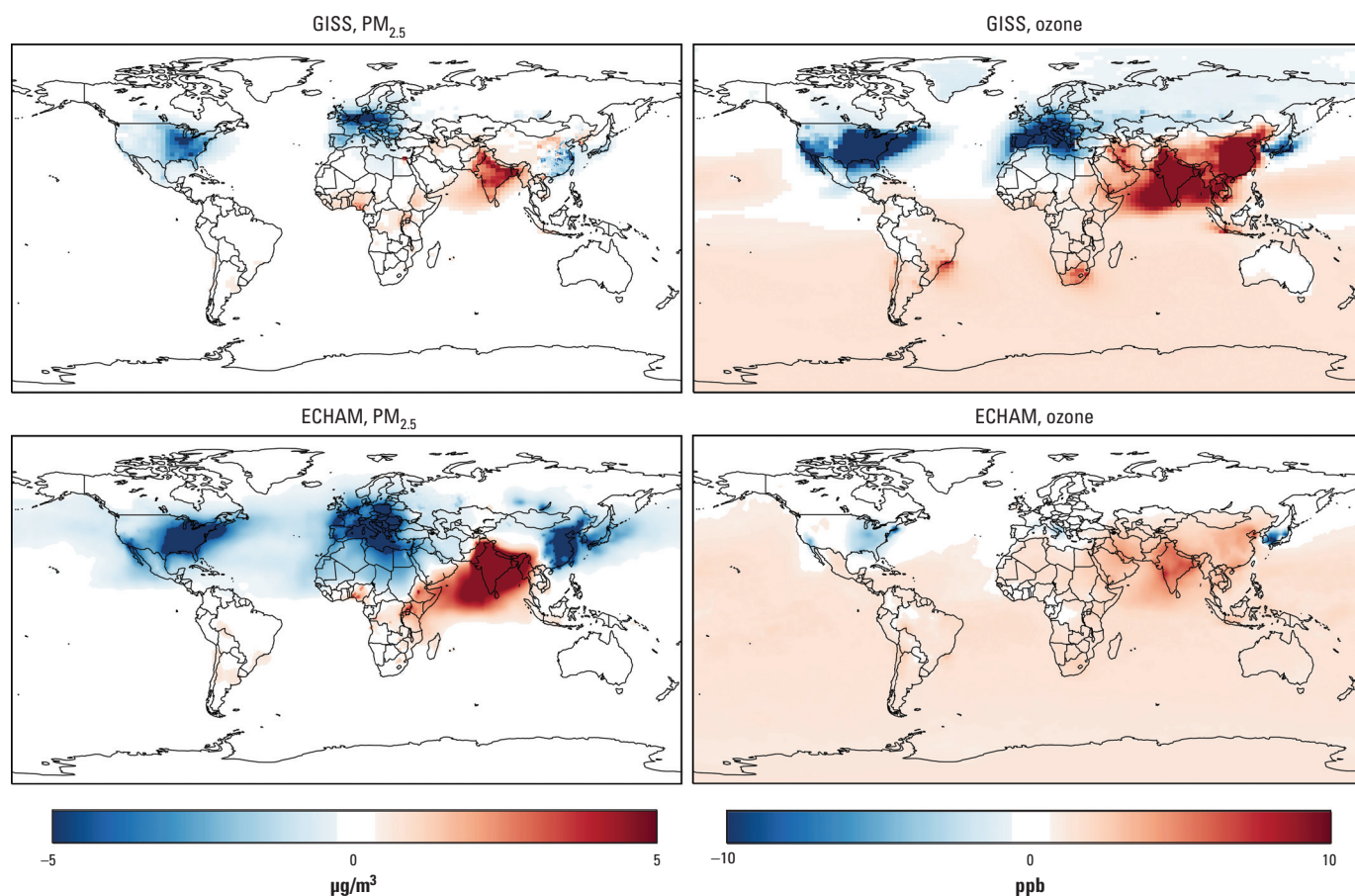


Figure 1. Estimated changes in annual average $PM_{2.5}$ ($\mu\text{g}/\text{m}^3$) and seasonal (6-month) average 1-hr daily maximum ozone (ppb) concentration for the 2030 reference scenario relative to 2005, based on the GISS and the ECHAM models.

these results were not available for the expert elicitation. Therefore, we examined the effect of these RRs in a sensitivity analysis only. Other recent cohort studies have reported considerably larger estimated effect sizes than the expert mean judgment (e.g., Miller et al. 2007; Puett et al. 2009), suggesting that our approach is conservative. Although some BC-rich PM_{2.5} mixtures may be more toxic than other mixtures (Maynard et al. 2007; Smith et al. 2009), we assumed that all PM_{2.5} components and mixtures are equally toxic because evidence for differential toxicity is currently inconclusive.

For ozone, we used long-term RR estimates from the ACS cohort (Jerrett et al. 2009) based on a two-pollutant model that controlled for PM_{2.5}, in which ozone was significantly associated only with death from respiratory causes. For a 10-ppb increase in the seasonal (6-month) average of 1-hr daily maximum ozone, the RR of respiratory disease was 1.04 (95% CI: 1.010, 1.067). The study by Jerrett et al. (2009) was the first

major study to find a significant positive relationship between chronic ozone exposure and mortality in a general population; biological plausibility for this result is supported by evidence from toxicology and human exposure studies showing that ozone affects airway inflammation, pulmonary function, and asthma induction and exacerbation (National Resource Council 2008). Global extrapolation of U.S.-based RR estimates for both PM_{2.5} and ozone is supported by generally consistent short-term PM_{2.5} and ozone mortality relationships around the world (e.g., Health Effects Institute 2010).

We used simulated concentrations in the first model layer for surface concentrations, and used annual average concentrations for PM_{2.5} and the maximum 6-month average of the 1-hr daily maximum for ozone, consistent with the epidemiology studies. We projected population growth (global population is projected to increase to 8.4 billion in 2030) based on the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios

(SRES) B2 scenario, which is near the center of projected population growth estimates for the different SRES scenarios (Intergovernmental Panel on Climate Change 2000). We estimated mortality only for the fraction of the population ≥ 30 years of age to be consistent with the age range of the ACS cohort, and we used present-day baseline mortality and YLL rates from the World Health Organization as described previously by Anenberg et al. (2010).

Results

Impacts of the future reference scenario. Both the GISS and ECHAM models indicated that PM_{2.5} and ozone concentrations would change dramatically, and with great spatial variability around the world, in the 2030 reference scenario relative to baseline estimates for 2005 (Figure 1). Projected concentration changes are solely due to emission changes because meteorology was held constant. Changes in climate would also impact concentrations to a lesser degree (e.g., Jacobson 2008).

We estimated that these concentration changes would substantially affect air pollution-related mortality around the world. Unless otherwise specified, ranges reported for expected changes in mortality and YLL represent the lowest and highest 95% CI bounds estimated using either the GISS or the ECHAM model, where the 95% CIs reflect uncertainty in the CRF. We expect that regulations that are currently in place or planned in North America and Europe will reduce PM_{2.5} and ozone concentrations substantially, resulting in 0.1–0.8 million avoided PM_{2.5}-related deaths per year (0.5–4.8 million YLL) in 2030, with the majority of avoided deaths in Europe [Figure 2; see also Supplemental Material, Figures 4 and 5 (<http://dx.doi.org/10.1289/ehp.1104301>)]. Regulations are also expected to reduce PM_{2.5} concentrations in East Asia, Southeast Asia, and the Pacific, resulting in 0.1–1.1 million avoided PM_{2.5}-related deaths (0.4–7.7 million YLL) annually, based on 2030 population projections. However, we estimated

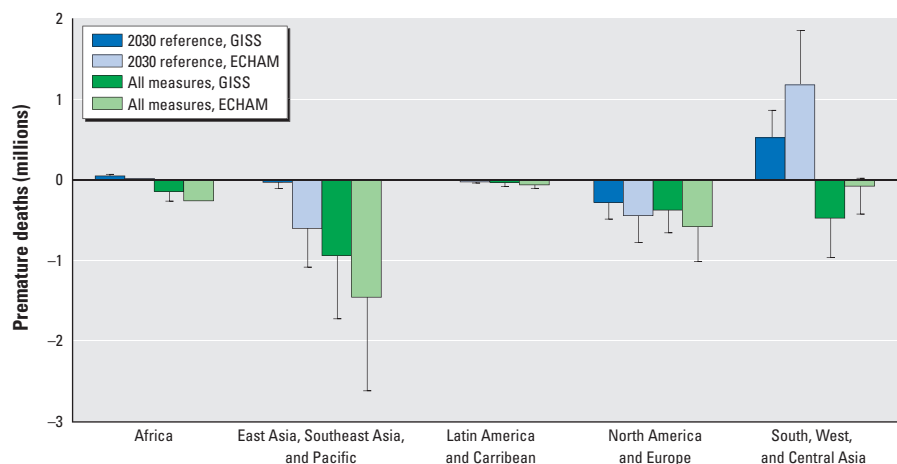


Figure 2. Estimated changes in premature PM_{2.5}-related mortality (cardiopulmonary and lung cancer deaths) and ozone-related mortality (respiratory deaths) for the 2030 reference scenario and assuming implementation of methane plus BC group 1 and BC group 2 (all) measures relative to 2005, based on 2030 population projections. 95% CIs reflect uncertainty in the CRF only.

Table 2. Global simple and population-weighted (Pop-wt) average reductions in annual average PM_{2.5} (μg/m³) and maximum 6-month average 1-hr daily maximum ozone (ppb) concentrations, avoided PM_{2.5} cardiopulmonary and lung cancer deaths and ozone respiratory deaths (millions), and avoided YLL (millions) based on 2030 population projections for increasingly stringent mitigation policies relative to the baseline scenario for 2030.

Result	Methane measures		Methane and BC group 1 measures		Methane, BC group 1, and BC group 2 measures	
	PM _{2.5}	Ozone	PM _{2.5}	Ozone	PM _{2.5}	Ozone
Simple average						
GISS	-0.01	3.08	0.15	5.34	0.22	5.66
ECHAM	-0.03	3.60	0.18	4.00	0.27	3.92
Pop-wt average						
GISS	-0.03	2.82	2.90	9.95	3.98	11.0
ECHAM	-0.12	4.09	3.59	4.96	4.92	4.71
Avoided deaths						
GISS	-0.02 (-0.01, -0.03)	0.07 (0.02, 0.11)	1.39 (0.46, 2.47)	0.28 (0.09, 0.47)	1.93 (0.63, 3.48)	0.31 (0.10, 0.52)
ECHAM	-0.06 (-0.02, -0.11)	0.10 (0.03, 0.17)	1.74 (0.57, 3.12)	0.13 (0.04, 0.21)	2.42 (0.78, 4.40)	0.12 (0.04, 0.20)
Avoided YLL						
GISS	-0.12 (-0.04, -0.21)	0.61 (0.20, 1.01)	11.8 (3.85, 21.0)	2.54 (0.82, 4.28)	16.2 (5.25, 29.3)	2.81 (0.90, 4.74)
ECHAM	-0.59 (-0.20, -1.01)	0.94 (0.31, 1.56)	14.9 (4.86, 26.6)	1.15 (0.38, 1.92)	20.5 (6.63, 37.4)	1.06 (0.35, 1.76)

95% CIs (shown in parentheses) reflect uncertainty in the CRFs for PM_{2.5}- and ozone-related mortality only. Estimates are based on simulations using the GISS and ECHAM models.

that increased ozone concentrations in East Asia, Southeast Asia, and the Pacific would cause 0–0.2 million additional premature ozone-related deaths (0.1–1.4 million YLL) per year. In addition, increased PM_{2.5} and ozone concentrations in South, West, and Central Asia resulting from rapid emissions growth would cause an estimated 0.1–1.8 million (1.2–15.9 million YLL) additional PM_{2.5}-related premature deaths and 0–0.2 million

(0.1–2.4 million YLL) additional ozone-related premature deaths annually.

Benefits of the mitigation measures. Relative to the 2030 reference scenario, implementing the methane measures (Table 1) would decrease seasonal (6-month) average 1-hr daily maximum ozone concentrations by 3–4 ppb (Table 2 and Figure 3). Projected ozone concentrations decreased fairly evenly across the globe due to the relatively longer lifetime of

methane compared with other ozone precursors (e.g., NO_x, VOCs). However, simulated annual average PM_{2.5} concentrations increased slightly from northern Africa to the Indian subcontinent in response to the methane measures due to particle formation resulting from changes in oxidant concentrations (Table 2 and Figure 4), as demonstrated previously by West et al. (2006). However, when BC and methane measures were applied together, these increases

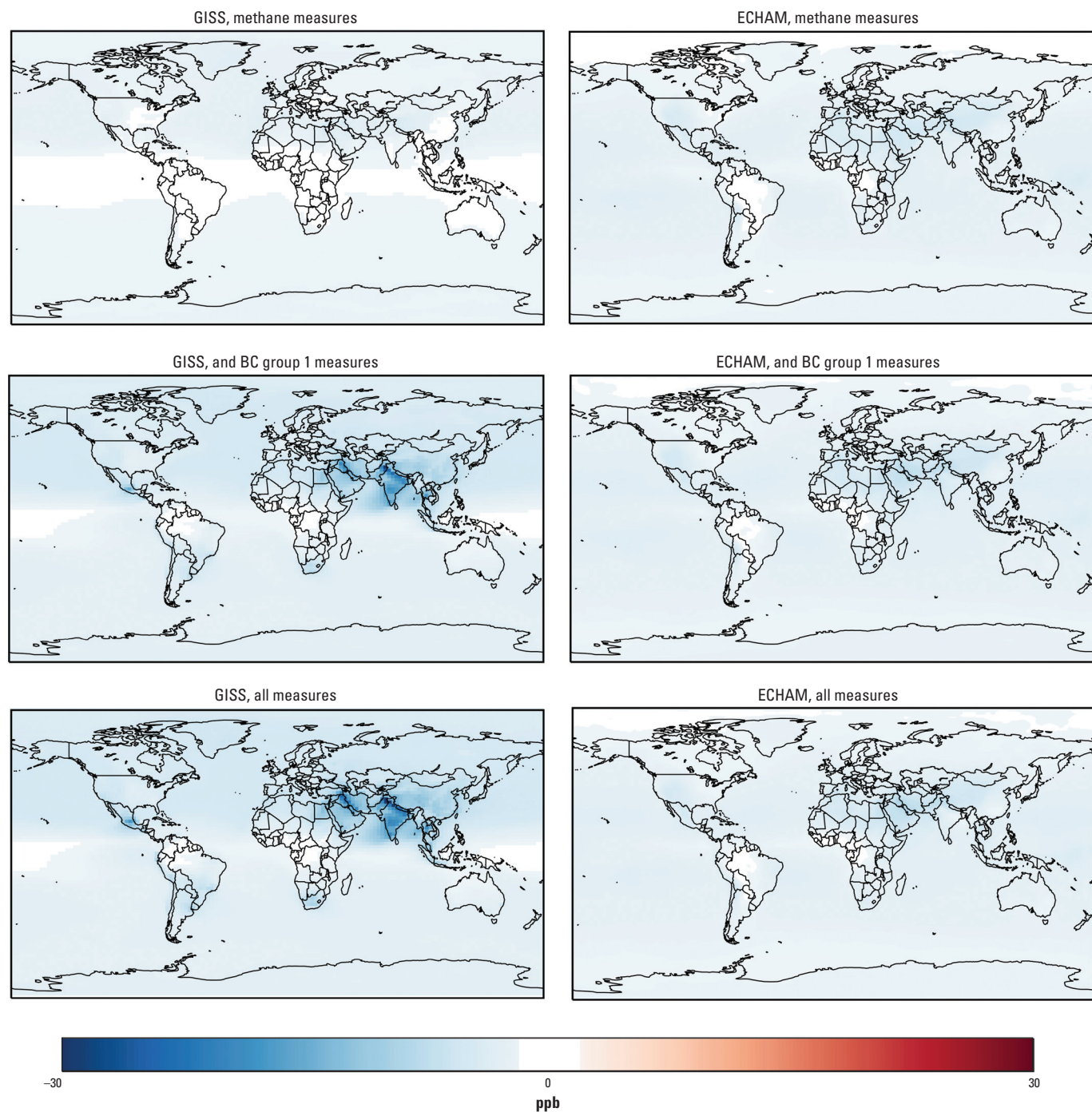


Figure 3. Estimated changes in seasonal (6-month) average 1-hr daily maximum ozone concentration (ppb) in 2030 for successive implementation of methane measures, methane plus BC group 1 measures, and methane plus BC group 1 and BC group 2 (all) measures, relative to the 2030 reference scenario, based on the GISS and the ECHAM models.

were projected only by the ECHAM model and were limited to a small area off the coast of eastern Africa and India. Adding the BC measures would reduce population-weighted $\text{PM}_{2.5}$ concentrations by 4–5 $\mu\text{g}/\text{m}^3$ compared with the 2030 reference scenario. Adding BC measures would also decrease ozone concentrations due to reductions in committed ozone precursors, but GISS projected larger reductions (11 ppb reduction when methane and BC measures were applied together) than did ECHAM (5 ppb reduction). Projected reductions in ozone concentrations resulting from

the BC measures were localized near the emissions sources (primarily in South and East Asia where emissions are largest) because of the short atmospheric lifetime of the ozone precursors that are affected by the BC measures [NO_x and CO; see Supplemental Material, Figure 3 (<http://dx.doi.org/10.1289/ehp.1104301>)]. Spatial patterns of simulated concentration changes were similar for both models, but GISS projections for ozone were more sensitive to precursors that would be affected by BC measures, whereas ECHAM projected greater reductions in ozone in response to the methane

measures and greater reductions in $\text{PM}_{2.5}$ in response to BC measures.

We estimated that implementing all measures would avoid 0.6–4.4 million $\text{PM}_{2.5}$ -related deaths (5.3–37.4 million YLL) and 0.04–0.52 million ozone-related deaths (0.35–4.7 million YLL) in 2030 [Table 2; see also Supplemental Material, Figures 6–9 (<http://dx.doi.org/10.1289/ehp.1104301>)]. For both models, > 80% of the estimated mortality benefits from implementation of all three groups of measures would occur in Asia, where large populations are exposed to high

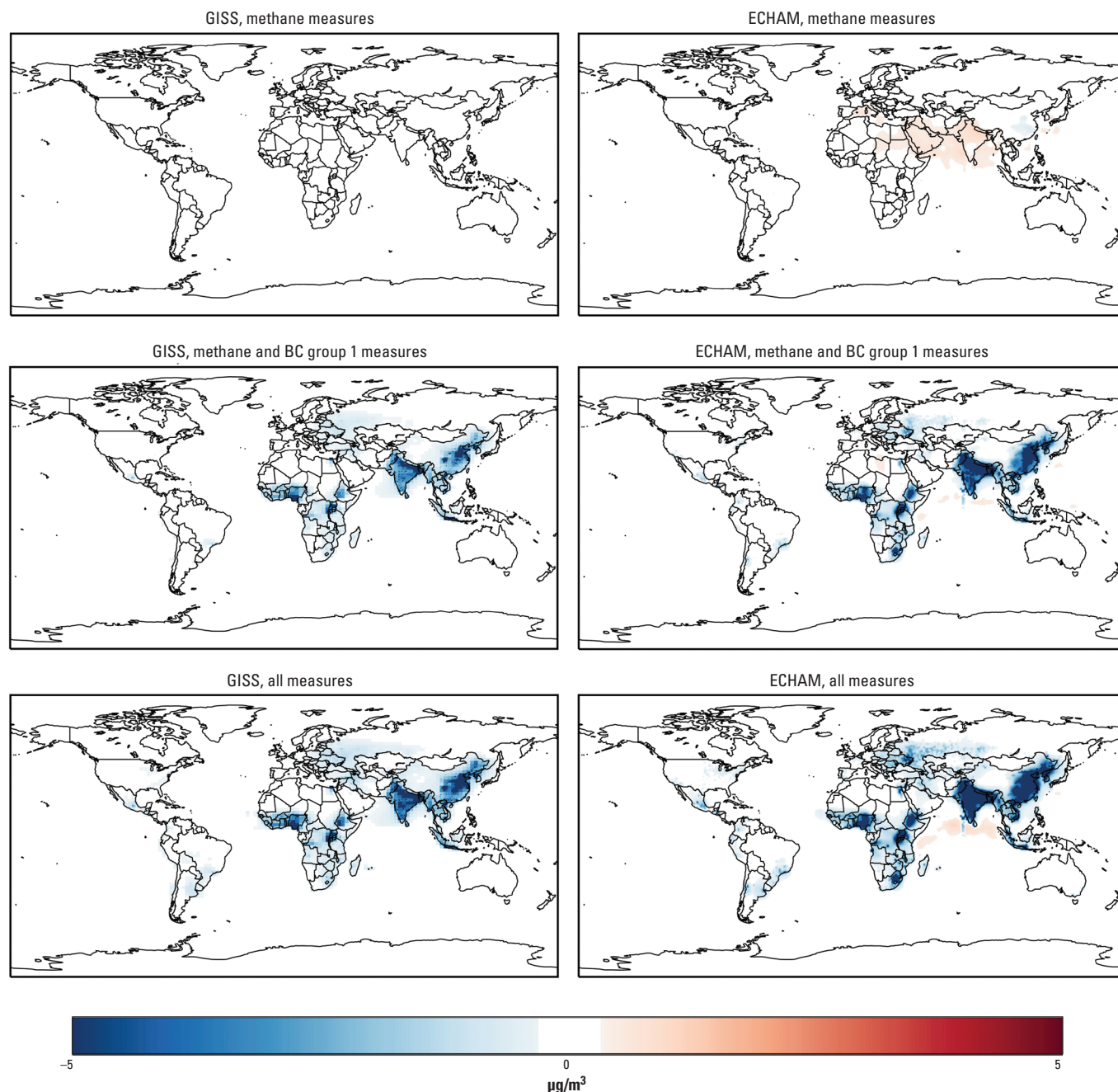


Figure 4. Estimated changes in annual average $\text{PM}_{2.5}$ concentration ($\mu\text{g}/\text{m}^3$) in 2030 for successive implementation of methane measures, methane plus BC group 1 measures, and methane plus BC group 1 and BC group 2 (all) measures, relative to the 2030 reference scenario, based on the GISS and the ECHAM models.

concentrations (Table 3). BC groups 1 and 2 measures (four technological measures for reducing emissions of incomplete combustion and three nontechnical measures to reduce the most polluting activities, respectively) would account for 72% and 26% of avoided deaths globally for either model. In contrast, estimated global mortality benefits of the methane measures were an order of magnitude smaller than those of the BC measures (approximately 2%), because of reductions of non-methane ozone precursor and organic carbon emissions associated with implementation of the BC measures and because of stronger relationships of PM_{2.5} with mortality. The estimated contribution of each policy measure to the total mortality benefit in each region generally followed the global contributions. When low-carbon CO₂ measures (decrease in use of fossil fuel) were included in both the reference and policy scenarios, estimates showed approximately 10% fewer avoided deaths in East Asia, Southeast Asia, and the Pacific and in South, West, and Central Asia (see Supplemental Material, Figure 10 (<http://dx.doi.org/10.1289/ehp.1104301>)). Implementing the methane and BC measures would reduce mortality substantially in all regions, and in some regions (Africa and South, West, and Central Asia) would reverse trends of increasing mortality due to air pollution (Figure 2).

Sensitivity analysis. We examined the effect of varying CRF assumptions on estimated avoided deaths from implementing all methane and BC measures (Figure 5). In the main results (case 1), we excluded dust and sea salt because evidence for toxicity of these components is weaker than that for particulate products of incomplete combustion. Including dust and sea salt would have increased estimated PM_{2.5} concentrations from a maximum of 62–73 µg/m³ (in the main results) to a maximum of 269–451 µg/m³. Whereas linearity of the CRF has been demonstrated up to 30 µg/m³ in the ACS study (Krewski et al. 2009) and up to 40 µg/m³ in the Harvard Six Cities study (Laden et al. 2006), some evidence suggests that the PM_{2.5} mortality relationship may flatten at high concentrations (e.g., Pope et al. 2009). We therefore examined several sensitivity cases in which the shape of the CRF was varied. Case 1 represented our baseline assumptions of linear CRFs from Pope et al. (2002) multiplied by 1.8 to scale up to the mean of the expert elicitation (Roman et al. 2008), that is, that cardiopulmonary and lung cancer mortality would increase by 1.6% and 2.4% with each 1-µg/m³ increase in PM_{2.5}, as in the main results (case 1). For case 2 we used log CRFs from Pope et al. (2002), multiplied by 1.8, such that the slopes of the relation between log-transformed PM_{2.5} concentration and cardiopulmonary and lung cancer mortality, respectively, were 0.2794 and

0.4180 (0.1552 and 0.2322 prior to scaling, as reported by Cohen et al. 2004). Case 3 was identical to case 2, except the log CRFs were modified to be linear below 7 µg/m³. Cases 4 and 5 were identical to cases 2 and 3 except they included dust and sea salt in estimated total PM_{2.5} concentrations. Because dust and sea salt were not significantly affected by the mitigation measures, using linear functions with dust and sea salt produced results that were similar to case 1. Two additional sensitivity cases examined the effect of using linear CRFs from the latest ACS reanalysis in which cardiopulmonary and lung cancer mortality

increased by 1.3% and 1.4%, respectively, with each 1-µg/m³ increase in PM_{2.5} (Krewski et al. 2009; case 6) and linear CRFs from the latest Harvard Six Cities reanalysis in which cardiopulmonary and lung cancer mortality increased by 2.8% and 2.7% with each 1-µg/m³ increase in PM_{2.5} (Laden et al. 2006; case 7). The significantly higher RR estimates reported by Laden et al. (2006) are still lower than estimates from other studies with less exposure error (e.g., Puett et al. 2009).

Compared with regional avoided deaths estimated using a linear function, those estimated using log functions without dust and sea

Table 3. Distributions of estimated numbers of avoided premature deaths according to policy measures and world regions, relative to the 2030 reference scenario.

Region	Percent of avoided deaths attributed to each group of policy measures ^a			Percent of all avoided deaths resulting from implementation of policy measures ^b		
	Methane	BC Group 1	BC Group 2	Methane	Methane and BC Group 1	Methane, BC Group 1 and BC Group 2
Global						
GISS	2.36	72.09	25.55			
ECHAM	1.62	72.09	26.29			
Africa						
GISS	3.62	74.36	22.01	12.77	8.71	8.32
ECHAM	2.78	72.88	24.34	17.84	10.68	10.40
East Asia, Southeast Asia, and Pacific						
GISS	2.22	68.52	29.26	38.14	38.48	40.50
ECHAM	6.29	64.27	29.45	130.84	32.34	33.79
Latin America and Caribbean						
GISS	9.67	64.36	25.96	7.37	1.79	1.80
ECHAM	12.0	54.71	33.26	13.72	1.68	1.85
North America and Europe						
GISS	6.53	68.76	24.70	11.94	4.36	4.31
ECHAM	3.81	60.63	35.56	12.29	4.58	5.24
South, West, and Central Asia						
GISS	1.56	75.50	22.94	29.78	46.66	45.08
ECHAM	-2.49	79.23	23.26	-74.69	50.73	48.72

^aThe individual impact of each group of policy measures is estimated based on the difference in mortality with the implementation of the increasingly stringent policy scenarios; the total for each row equals 100%. ^bProportions of avoided deaths associated with the successive implementation of the policy scenarios; column totals for each model (GISS or ECHAM) equal 100%.

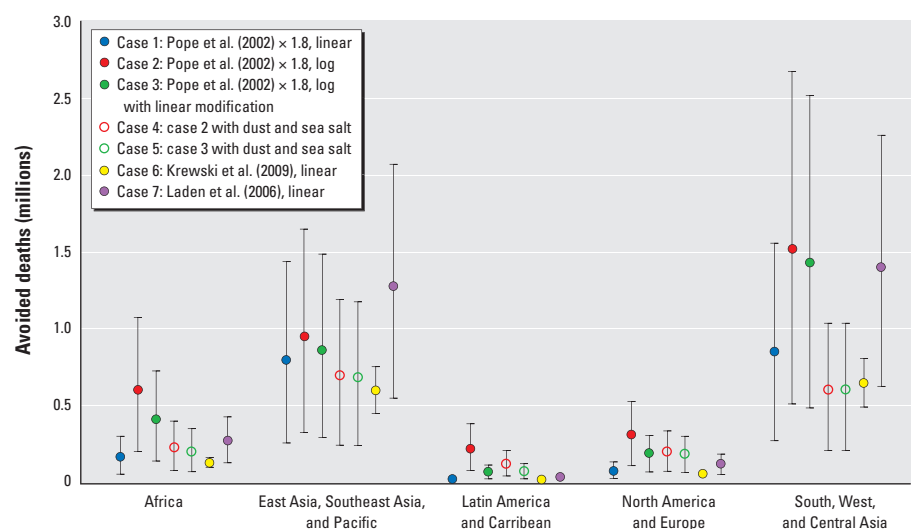


Figure 5. Estimated annual PM_{2.5}-related cardiopulmonary and lung cancer deaths assuming implementation of methane plus BC group 1 and BC group 2 (all) measures relative to the 2030 reference scenario using concentrations simulated by the GISS model and different assumptions for the CRF, based on 2030 population projections.

salt (case 2) were 1.2–8.3 times higher and had larger differences in the least polluted regions due to a higher marginal impact of $PM_{2.5}$ on mortality for the log functions at low concentrations. When dust and sea salt were included in $PM_{2.5}$ concentrations (case 4), estimates were 12–29% lower in Asia (where $PM_{2.5}$ concentrations are high) and 1.4–4.6 times higher in less-polluted regions. Modifying the functions to be linear at low concentrations (cases 3 and 5) reduced the inflated estimates that occurred in relatively unpolluted regions when log functions were used. Using RR estimates from Krewski et al. (2009; case 6) reduced estimated deaths by approximately 25% relative to the main results. Although RR estimates by Krewski et al. (2009) are higher than those reported by Pope et al. (2002), we multiplied CRFs from Pope et al. (2002) by 1.8 for the main results. Using RR estimates from the Harvard Six Cities cohort (case 7) increased estimates by approximately 60%. Uncertainty ranges were large for each case, with the exception of case 6, because Krewski et al. (2009) estimated more precise RRs than the other studies. However, confidence intervals overlapped among estimates from all of the sensitivity analyses.

Discussion and Conclusion

We estimated the potential future air quality and health benefits resulting from implementing 14 specific methane and BC emission control measures selected for their near-term climate benefits (Table 1). We estimate that these measures could reduce global population-weighted average surface $PM_{2.5}$ and ozone concentrations by 3.98–4.92 $\mu g/m^3$ (23.0–33.7%) and 4.71–11.0 ppb (6.5–17.0%), respectively, and avoid 0.6–4.4 and 0.04–0.52 million annual premature deaths globally in 2030. More than 80% of the health benefits of these measures are estimated to occur in Asia. Based on our estimates, avoided deaths would represent 1–8% of cardiopulmonary and lung cancer deaths among those ≥ 30 years of age and 1–7% of all deaths for all ages, assuming constant baseline mortality rates. BC mitigation measures would account for approximately 98% of the estimated deaths avoided, because BC mitigation would also reduce emissions of non-methane ozone precursors and organic carbon and because concentration–response relationships are stronger for $PM_{2.5}$ than for ozone. Our estimates are consistent with previous health impact assessments of BC and methane reductions (Anenberg et al. 2011; Shindell et al. 2011; West et al. 2006) after accounting for methodological differences [see Supplemental Material, p. 16 (<http://dx.doi.org/10.1289/ehp.1104301>)].

We used two global composition–climate models (GISS and ECHAM) to improve confidence in our results, and sensitivity analysis

indicated that our results and conclusions are not strongly dependent on assumptions for the CRF. However, we were unable to quantify other uncertainties associated with estimating air pollution mortality on a global scale, including uncertainties in the atmospheric model assumptions and inputs (e.g., emissions) and in estimates of population growth and baseline mortality rates. We applied U.S.-based CRFs globally, despite differences in concentrations, air pollutant mixtures, and exposure and population susceptibility characteristics. We assumed that all $PM_{2.5}$ mixtures are equally toxic, despite some evidence that BC-rich mixtures are more toxic than the average (e.g., Smith et al. 2009). These uncertainties may cause under- or overestimation in the results.

The benefits of implementing BC measures are likely to have been underestimated because we did not account for health benefits of reduced indoor exposure from the burning of solid fuel, which has been estimated to cause 1.6 million premature deaths annually (Smith et al. 2004). In addition, while we downscaled modeled BC and organic carbon concentrations to a finer resolution grid, observed BC concentrations near highly populated regions that rely on biomass combustion for cooking and heating are orders of magnitude higher than the grid mean values used here (Rehman et al. 2011). We also did not consider benefits from reductions in noncarbonaceous primary $PM_{2.5}$ components (e.g., fly ash) that may result from the BC mitigation measures. We estimate that including noncarbonaceous primary $PM_{2.5}$ components would reduce total $PM_{2.5}$ emissions by an additional 18% [see Supplemental Material, Figure 3 (<http://dx.doi.org/10.1289/ehp.1104301>)] but would have a smaller effect on $PM_{2.5}$ concentration changes (and associated mortality changes), because some $PM_{2.5}$ components included in the $PM_{2.5}$ definition are not emitted directly but are formed in the atmosphere. We did not estimate effects of air pollution on morbidity or infant mortality because of concerns about the quality and availability of concentration–response functions and baseline incidence data globally. We also did not consider health effects of climate change (e.g., direct effects of temperature), which vary across locations and are poorly understood. Finally, we held present-day baseline mortality rates constant to 2030, although economic development around the world is reducing mortality from infectious disease and increasing mortality due to chronic diseases that are more affected by air pollution. Hence the overall health benefits of these interventions are likely to be understated.

The UNEP/WMO assessment demonstrated that further implementation of methane and BC emissions control measures

currently employed in some parts of the world can slow the rate of climate change in the decades following implementation (Shindell et al. 2012; UNEP 2011). We conclude that these measures can also substantially benefit global public health, potentially reversing trends of increasing concentrations and air pollution-related mortality in Africa and South, West, and Central Asia. These estimated benefits are independent of CO_2 mitigation measures. Future research should include both indoor and outdoor concentration changes to quantify the full health and climate benefits of cook stove replacement, and should quantify the benefits and costs of each measure in individual countries or regions to support national-scale policy decisions.

REFERENCES

- Amann M, Bertok I, Borken-Kleefeld J, Cofala J, Heyes C, Hoglund-Isaksson L, et al. 2011. Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications. *Environ Modelling Software* 26:1489–1501.
- Anenberg SC, Horowitz LW, Tong DQ, West JJ. 2010. An estimate of the global burden of anthropogenic ozone and fine particulate matter on premature human mortality using atmospheric modeling. *Environ Health Perspect* 118:1189–1195.
- Anenberg SC, Talgo K, Arunachalam S, Dolwick P, Jang C, West JJ. 2011. Impacts of global, regional, and sectoral black carbon emission reductions on surface air quality and human mortality. *Atmos Chem Phys* 11:7253–7267.
- Ashmore MR. 2005. Assessing the future global impacts of ozone on vegetation. *Plant Cell Environ* 28:949–964.
- Cohen AJ, Anderson HR, Ostro B, Pandey KD, Krzyzanowski M, Künzli N, et al. 2004. Urban air pollution. In: *Comparative Quantification of Health Risks: Global and Regional Burden of Disease due to Selected Major Risk Factors* (Ezzati M, Lopez AD, Rodgers A, Murray CJL, eds). Geneva:World Health Organization, 1353–1434. Available: http://www.who.int/healthinfo/global_burden_disease/cra/en/ [accessed 24 April 2012].
- Cooke WF, Liouss C, Cachier H, Feichter J. 1999. Construction of a 1x1 fossil fuel emission data set for carbonaceous aerosol and implementation and radiative impact in the ECHAM4 model. *J Geophys Res* 104:22137–22162.
- European Union. 2010. Emissions from Heavy Duty Vehicles (Euro VI): Certification Rules. Available: http://europa.eu/legislation_summaries/environment/air_pollution/mi0029_en.htm [accessed 25 April 2012].
- European Union. 2011. Reduction of Pollutant Emissions from Light Vehicles. Available: http://europa.eu/legislation_summaries/environment/air_pollution/128186_en.htm [accessed 25 April 2012].
- Haines A, McMichael AJ, Smith KR, Roberts I, Woodcock J, Markandya A, et al. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: overview and implications for policy makers. *Lancet* 374:2104–2114.
- Health Effects Institute. 2010. Public Health and Air Pollution in Asia (PAPA): Coordinated Studies of Short-Term Exposure to Air Pollution and Daily Mortality in Four Cities. HEI Research Report 154. Boston:Health Effects Institute.
- Intergovernmental Panel on Climate Change. 2000. Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge, UK:Cambridge University Press.
- International Energy Agency. 2009. World Energy Outlook 2009. Paris:International Energy Agency.
- Jackson SC. 2009. Parallel pursuit of near-term and long-term climate mitigation. *Science* 326:526–527.
- Jacobson MZ. 2002. Control of fossil-fuel particulate black carbon and organic matter, possibly the most effective method of slowing global warming. *J Geophys Res* 107:4410; doi:10.1029/2001JD001376 [Online 15 October 2002].
- Jacobson MZ. 2008. On the causal link between carbon dioxide and air pollution mortality. *Geophys Res Lett* 35:L03809; doi:10.1029/2007GL031101 [Online 12 February 2008].
- Jacobson MZ. 2010. Short-term effects of controlling fossil-fuel

- soot, biofuel soot and gases, and methane on climate, Arctic ice, and air pollution health. *J Geophys Res* 115:D14209: doi:10.1029/2009JD013795 [Online 29 July 2010].
- Jerrett M, Burnett RT, Pope CA III, Ito K, Thurston G, Krewski D, et al. 2009. Long-term ozone exposure and mortality. *N Engl J Med* 360:1085–1095.
- Krewski D, Jerrett M, Burnett RT, Ma R, Hughes E, Shi Y, et al. 2009. Extended Follow-up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality. Boston:Health Effects Institute.
- Laden F, Schwartz J, Speizer FE, Dockery DW. 2006. Reduction in fine particulate air pollution and mortality: extended follow-up of the Harvard Six Cities study. *Am J Resp Crit Care Med* 173:667–672.
- MacCarty N, Ogle D, Still D, Bond T, Roden C. 2008. A laboratory comparison of the global warming impact of five major types of biomass cooking stoves. *Energy Sustainable Dev* 12:56–65.
- Maynard D, Coull BA, Gryparis A, Schwartz J. 2007. Mortality risk associated with short-term exposure to traffic particles and sulfates. *Environ Health Perspect* 115:751–755.
- Miller KA, Siscovick DS, Sheppard L, Shepherd K, Sullivan JH, Anderson GL, et al. 2007. Long-term exposure to air pollution and incidence of cardiovascular events in women. *N Engl J Med* 356:447–458.
- National Research Council. 2008. Estimating Mortality Risk Reduction and Economic Benefits from Controlling Ozone Air Pollution. Washington, DC:National Academies Press.
- Pope CA III, Burnett RT, Krewski D, Jerrett M, Shi Y, Calle EE, et al. 2009. Cardiovascular mortality and exposure to air-borne fine particulate matter and cigarette smoke: shape of the exposure-response relationship. *Circulation* 120:941–948.
- Pope CA III, Burnett RT, Thun MJ, Calle EE, Krewski D, Ito K, et al. 2002. Lung cancer, cardiopulmonary mortality, and long-term exposure to fine particulate air pollution. *JAMA* 287:1132–1141.
- Pozzoli L, Bey I, Rast S, Schultz MG, Stier P, Feichter J. 2008. Trace gas and aerosol interactions in the fully coupled model of aerosol-chemistry-climate ECHAM5-HAMMOZ: 1. Model description and insights from the spring 2001 TRACE-P experiment. *J Geophys Res* 113:D07308; doi:10.1029/2007JD009007 [Online 15 April 2008].
- Puett RC, Hart J, Yanosky JD, Paciorek C, Schwartz J, Suh H, et al. 2009. Chronic fine and coarse particulate exposure, mortality, and coronary heart disease in the Nurses' Health Study. *Environ Health Perspect* 117:1702–1706.
- Ramanathan V, Agrawal M, Akimoto H, Aufhammer M, Devotta S, Emberson L, et al. 2008. Atmospheric Brown Clouds: Regional Assessment Report with Focus on Asia. Nairobi, Kenya:United Nations Environment Programme.
- Ramanathan V, Carmichael G. 2008. Global and regional climate changes due to black carbon. *Nat Geosci* 1:221–227.
- Rehman IH, Ahmed T, Praveen PS, Kar A, Ramanathan V. 2011. Black carbon emissions from biomass and fossil fuels in rural India. *Atmos Chem Phys* 11:7289–7299.
- Roman HA, Walker KD, Walsh TL, Conner L, Richmond HM, Hubbell BJ, et al. 2008. Expert judgment assessment of the mortality impact of changes in ambient fine particulate matter in the U.S. *Environ Sci Technol* 42:2268–2274.
- Shindell DT, Faluvegi G, Unger N, Aguilar E, Schmidt GA, Koch DM, et al. 2006. Simulations of preindustrial, present-day, and 2100 conditions in the NASA GISS composition and climate model G-PUCCINI. *Atmos Chem Phys* 6:4427–4459.
- Shindell D, Faluvegi G, Walsh M, Anenberg SC, Van Dingenen R, Muller NZ, et al. 2011. Climate, health, agricultural and economic impacts of tighter vehicle-emission standards. *Nat Clim Change* 1:59–66.
- Shindell D, Kuylenstierna JCI, Vignati E, Van Dingenen R, Amann M, Klimont Z, et al. 2012. Simultaneously mitigating near-term climate change and improving human health and food security. *Science* 335:183–189.
- Smith KR, Jerrett M, Anderson HR, Burnett RT, Stone V, Derwent R, et al. 2009. Public health benefits of strategies to reduce greenhouse-gas emissions: health implications of short-lived greenhouse pollutants. *Lancet* 374:2091–2103.
- Smith KR, Mehta S, Maeusezahl-Feuz M. 2004. Indoor air pollution from household use of solid fuels. In: *Comparative Quantification of Health Risks: Global and Regional Burden of Disease Attribution to Selected Major Risk Factors* (Ezzati M, Lopez AD, Rodgers A, Murray CJL, eds). Geneva:World Health Organization, 1435–1493.
- UNEP (United Nations Environment Programme). 2011. Opportunities to Limit Near-Term Climate Change: An Integrated Assessment of Black Carbon and Tropospheric Ozone and Its Precursors. Nairobi, Kenya:United Nations Environment Programme and World Meteorological Organization.
- West JJ, Fiore AM, Horowitz LW, Mauzerall DL. 2006. Global health benefits of mitigating ozone pollution with methane emission controls. *Proc Natl Acad Sci USA* 103:3988–3993.
- West JJ, Szopa S, Hauglustaine DA. 2007. Human mortality effects of future concentrations of tropospheric ozone. *C R Geosci* 339:775–783.

Supplemental Material:

Global Air Quality and Health Co-Benefits of Mitigating Near-Term Climate Change through Methane and Black Carbon Emission Controls

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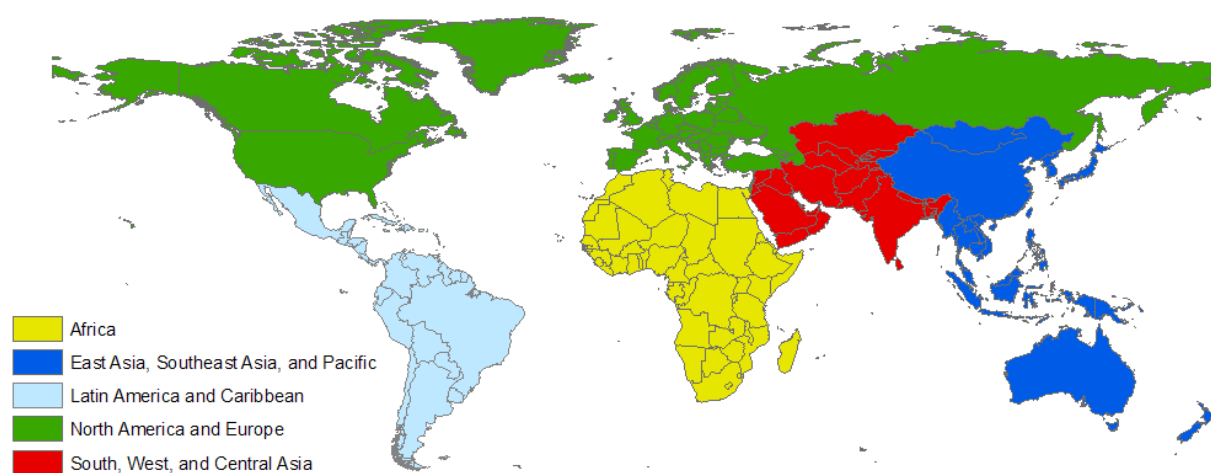
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Regional definitions



Supplemental Material, Figure 1. Regional definitions used in this analysis.

Selection of the mitigation measures

Most pollutants are not emitted in isolation, but rather in a mixture of species that have different impacts on near-term climate change, some of them heating and others cooling. In addition, most mitigation measures impact the mixture of emissions from a source rather than individual pollutants alone. The overall effect of each mitigation measure depends on the net radiative forcing resulting from changes in emissions of all species. Since the net climate effect can be warming or cooling, we identify a small portfolio of measures with the largest potential reductions in global radiative forcing in 2030. Thus, measures that would increase radiative forcing are excluded from this study.

As described in further detail by the UNEP/WMO Assessment (UNEP 2011) and Shindell et al. (2012), approximately 2000 mitigation measures in 108 world regions in the IIASA GAINS model were screened for their potential climate benefits using the GWP100 metric (see Supplemental Material, Table 1). The measures were then ranked according to their net carbon dioxide equivalence (CO_2eq) accounting for all affected pollutants (i.e., methane, CO, BC, OC, SO_2 , NO_x , NMVOCs and CO_2). Results of the GWP evaluation are minimally sensitive to the time horizon since CO_2 emissions were largely unaffected and the effects for all short-lived compounds would change similarly. We found that all measures targeting methane would result in net radiative forcing benefits, while measures to reduce BC differed in estimated net positive or negative climate impacts due to impacts on co-emitted CO and other species. No attempt was made to optimize the selected measures based on health, vegetation, and crop impacts; rather, we simply quantify the health co-benefits of the measures selected for climate benefits.

Supplemental Material, Table 1. Values and sources of GWP100s for each species used for the screening of mitigation measures in the GAINS model (source: UNEP 2011). Note: The GWPs for CO and methane include the indirect effects of ozone.^a

Species	Mean value	Reference
CO₂	1	IPCC (2007)
CH₄	25	IPCC (2007)
CO	1.9	IPCC (2007)
VOC	3.4	IPCC (2007)
BC	680	Bond and Sun (2005)
SO₂	-40	Fuglestad et al. (2009)
OC	-69	Fuglestad et al. (2009)

^aGWP100 values represent the radiative forcing of a unit mass of the species given relative to that of CO_2 for a 100 year time horizon.

Emission changes

The 2030 reference scenario assumes significant growth in fossil fuel use relative to 2005, leading to increases in estimated CO₂ (45%) and methane (27%) emissions (See Supplemental Material, Table 2 and Figure 2). However, abatement measures prescribed in current legislation are projected to reduce air pollutant emissions, varying by pollutant and region. While total primary PM_{2.5} emissions (includes non-carbonaceous PM_{2.5}, e.g. fly ash) remain approximately constant, BC and OC are estimated to decline by a few percent, mostly due to emission reductions in North America & Europe and Northeast Asia, Southeast Asia & Pacific, where residential coal burning is expected to decline. While projected NO_x (-3%) and SO₂ (-19%) emissions are reduced significantly in North America and Europe, emissions in other regions are expected to grow or remain constant. Asia is projected to contribute most to total PM_{2.5} (>60%), SO₂ (65%), and NO_x (>50%) emissions in 2030.

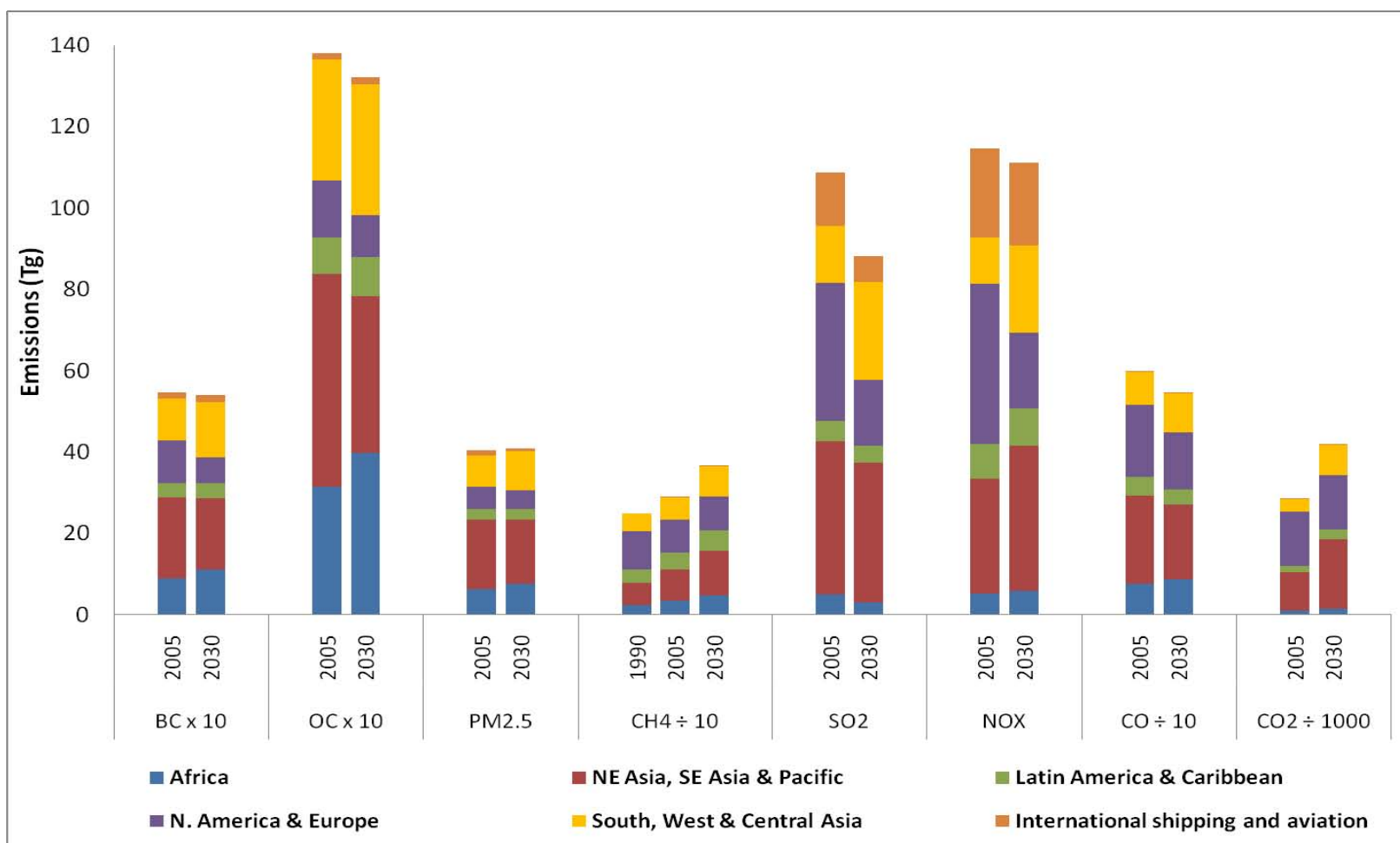
The methane measures reduce estimated global anthropogenic methane emissions by 38%, with little impact on other species (See Supplemental Material, Figure 3). BC measures together would reduce global anthropogenic BC emissions by 75%, primarily via biomass combustion controls and diesel particle filters. Measures targeting BC would also substantially reduce total primary PM_{2.5} (-50%, of which ~15% is non-carbonaceous, e.g. fly ash), OC (-79%), NO_x (-27%), and CO (-44%). Emissions of non-carbonaceous primary PM_{2.5} components, which we exclude from our PM_{2.5} definition, are projected to be reduced by ~18% of the magnitude of the BC and OC reduction. The BC measures would have little impact on SO₂ emissions since measures reducing sulfate (SO₄; which has a net cooling influence on climate) were largely excluded, as they would not deliver the climate benefit set as a goal in the assessment. Projected emissions are generally reduced most in Asia, followed by Africa. North America and Europe contribute relatively less to emission reductions, except for methane. We also examine the impacts of stabilizing greenhouse gases at 450 ppm of CO₂ equivalent, consistent with a global average temperature increase of ~2° C (IEA 2009). CO₂ measures would reduce SO₂ (-30%) and NO_x (-20%) but have little impact on the other species (~5% decline) since the major sources of CO₂ differ from those of methane and BC.

Supplemental Material, Table 2. Global anthropogenic emissions used in this study for the 2005 and 2030 reference cases, Tg a⁻¹. Source: GAINS model^a, EDGAR v4.1, and Lamarque et al. (2010) for international shipping and aviation (RCP8.5 scenario)

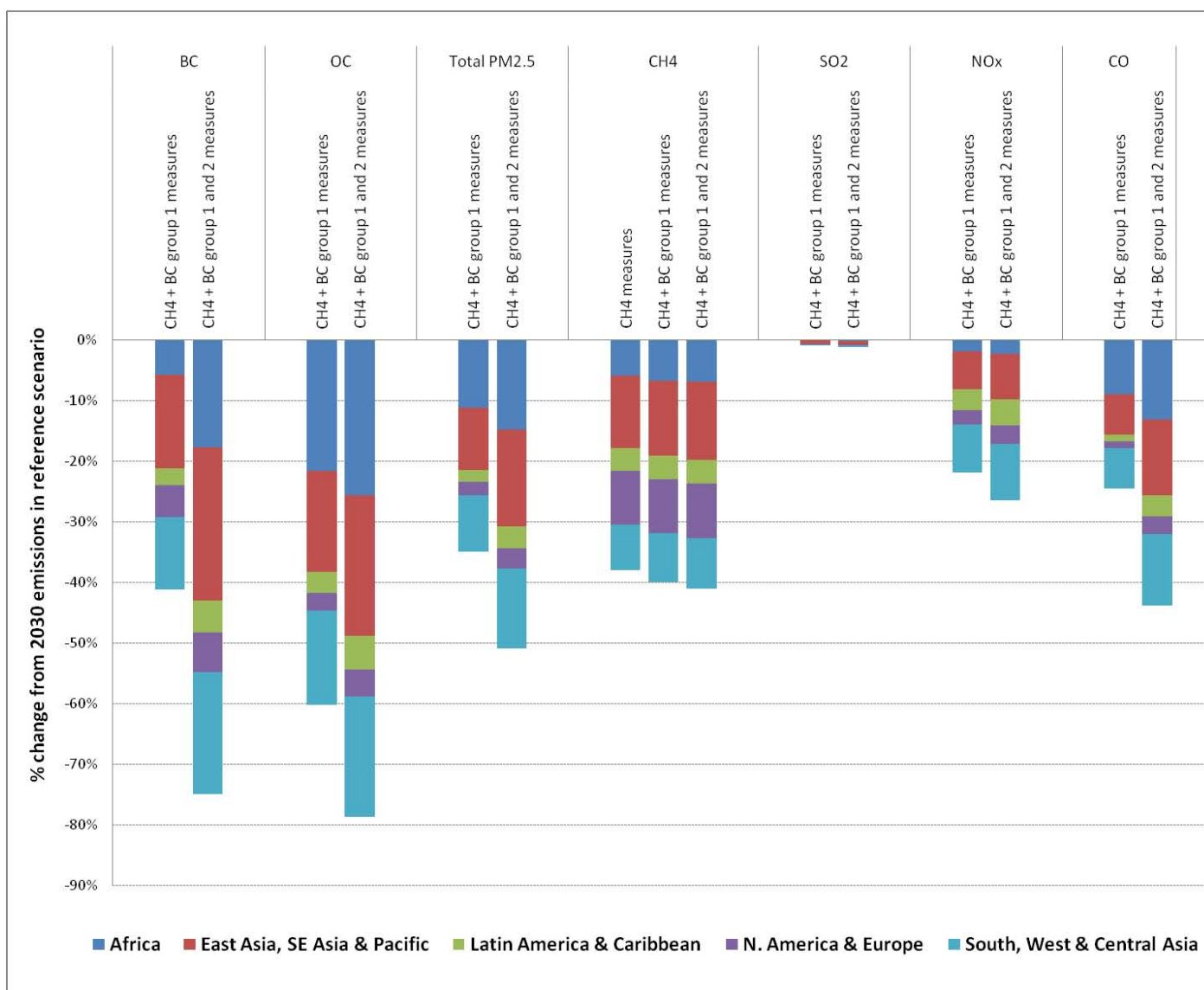
Species	Year	Region					
		Africa	NE Asia, SE Asia & Pacific	Latin America & Caribbean	N. America & Europe	South, West & Central Asia	Global
BC	2005	0.89	1.99	0.35	1.04	1.04	5.46
	2030	1.11	1.76	0.37	0.62	1.37	5.40
OC	2005	3.14	5.23	0.90	1.40	2.98	13.80
	2030	3.98	3.86	0.95	1.05	3.20	13.21
Total PM_{2.5}	2005	6.24	17.04	2.75	5.34	7.68	40.44
	2030	7.70	15.64	2.58	4.57	9.65	40.81
SO₂	2005	4.86	37.84	5.04	33.77	14.07	108.64
	2030	3.03	34.39	4.04	16.18	24.18	88.15
NO_x^b	2005	5.08	28.43	8.52	39.43	11.29	114.73
	2030	5.84	35.69	9.11	18.74	21.37	111.19
CH₄	2005	34.40	76.58	40.95	82.18	53.79	288.36
	2030	47.77	108.21	52.23	83.21	73.51	365.46
CO	2005	75.69	217.67	45.25	176.96	81.89	598.74
	2030	87.27	182.46	39.18	138.32	96.18	544.95
CO₂	2005	1.04	9.40	1.46	13.36	3.22	29.91
	2030	1.48	17.04	2.32	13.47	7.35	43.41

^a Except global NH₃ and NMVOC emissions from solvent use for all countries except Europe, China, and India, that originate from EDGAR v4.1

^b Reported as NO₂



Supplemental Material, Figure 2. Global anthropogenic emissions used in this study for the 2005 and 2030 reference cases, as in Supplemental Material, Table 2. To compare the emissions magnitudes of the various species on a uniform scale, BC and OC emissions are shown multiplied by 10, methane and CO emissions are divided by 10, and CO₂ emissions are divided by 1000.

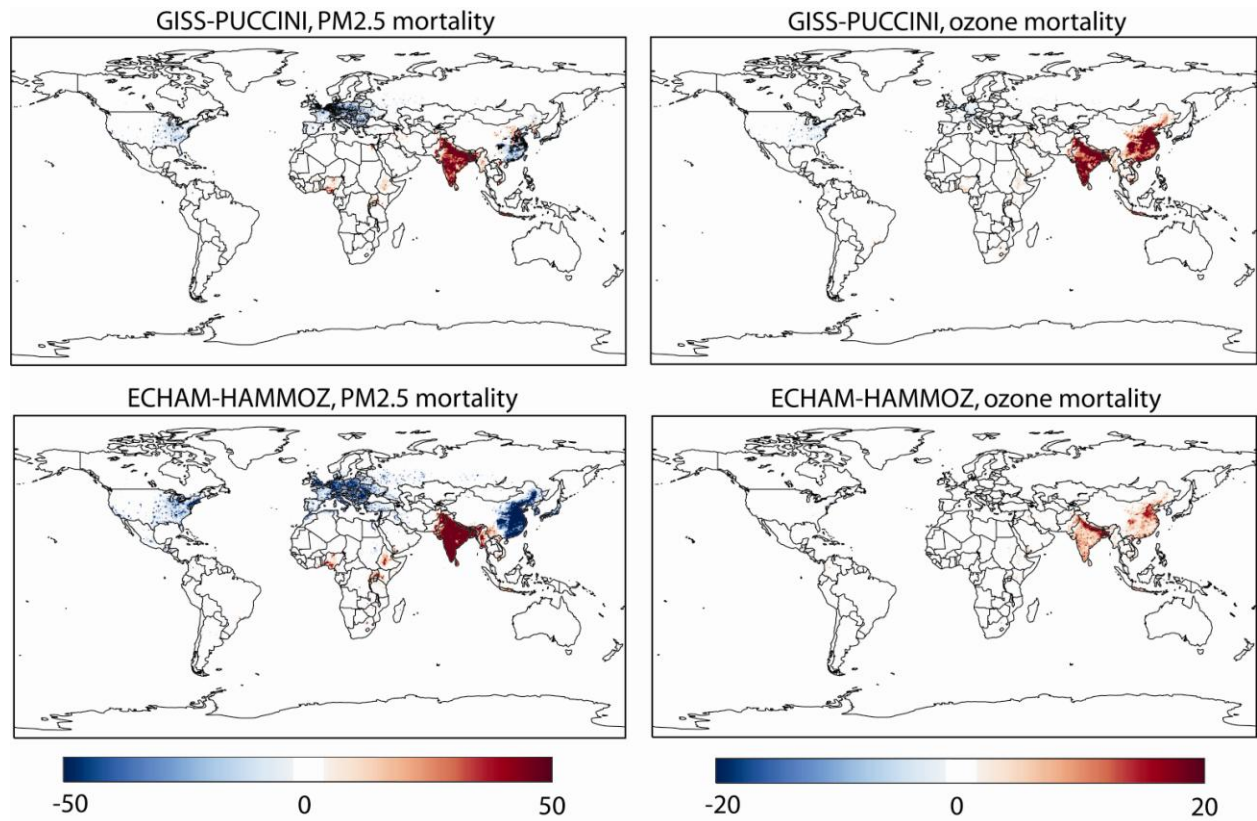


Supplemental Material, Figure 3. Percent change in emissions for the successive implementation of methane measures, methane plus BC Group 1 measures, and methane plus BC Group 1 and BC Group 2 measures, relative to the 2030 reference scenario, by region.

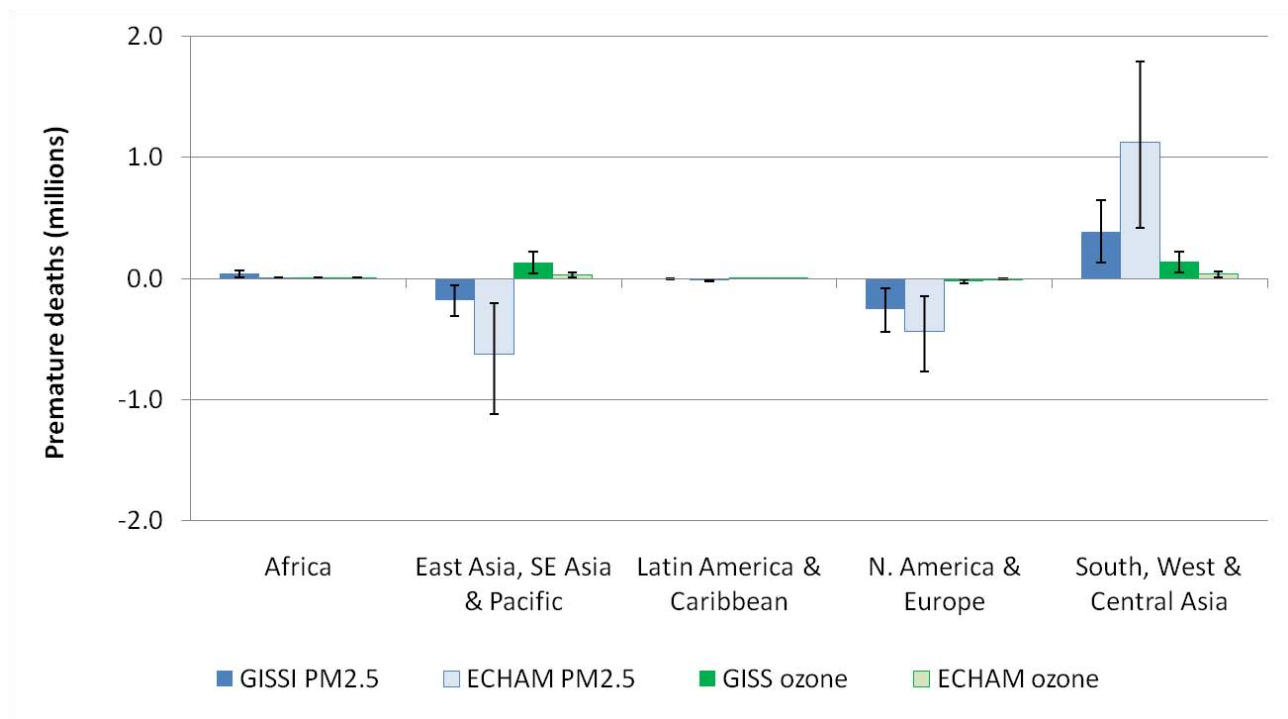
Supplemental Material, Table 3. Radiative forcing (W/m^2) for the successive implementation of methane measures, methane plus BC Group 1 measures, and methane plus BC Group 1 and BC Group 2 measures, relative to the 2030 reference, calculated by the GISS model (source: Shindell et al. 2012).

	Methane measures	Methane + BC Group 1 measures	Methane + BC Group 1 + BC Group 2 measures
Ozone	-0.10	-0.17	-0.19
Methane	-0.20	-0.20	-0.18
Aerosols - direct (BC, OC, sulfate, nitrate)	-0.01 (0.00, 0.00, -0.02, 0.00)	-0.06 (-0.10, 0.06, -0.02, 0.01)	-0.17 (-0.22, 0.07, -0.02, 0.01)
Aerosols - indirect and semi-direct	-	-0.14 ± 0.03	-0.16 ± 0.04
BC albedo (effective forcing x5)	-	-0.010 (-0.05)	-0.017 (-0.09)
Net	-0.32	-0.60	-0.77

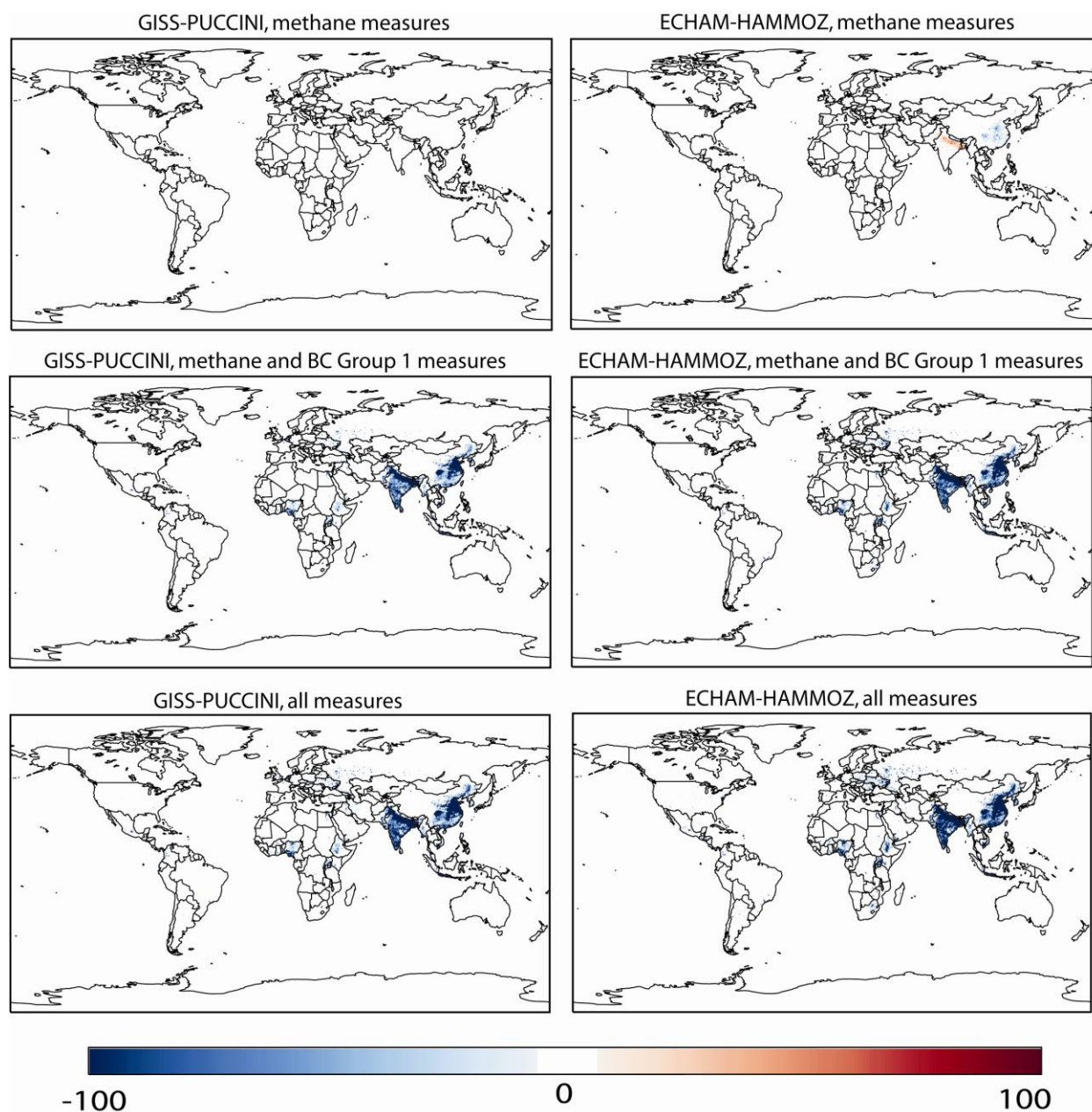
Additional results



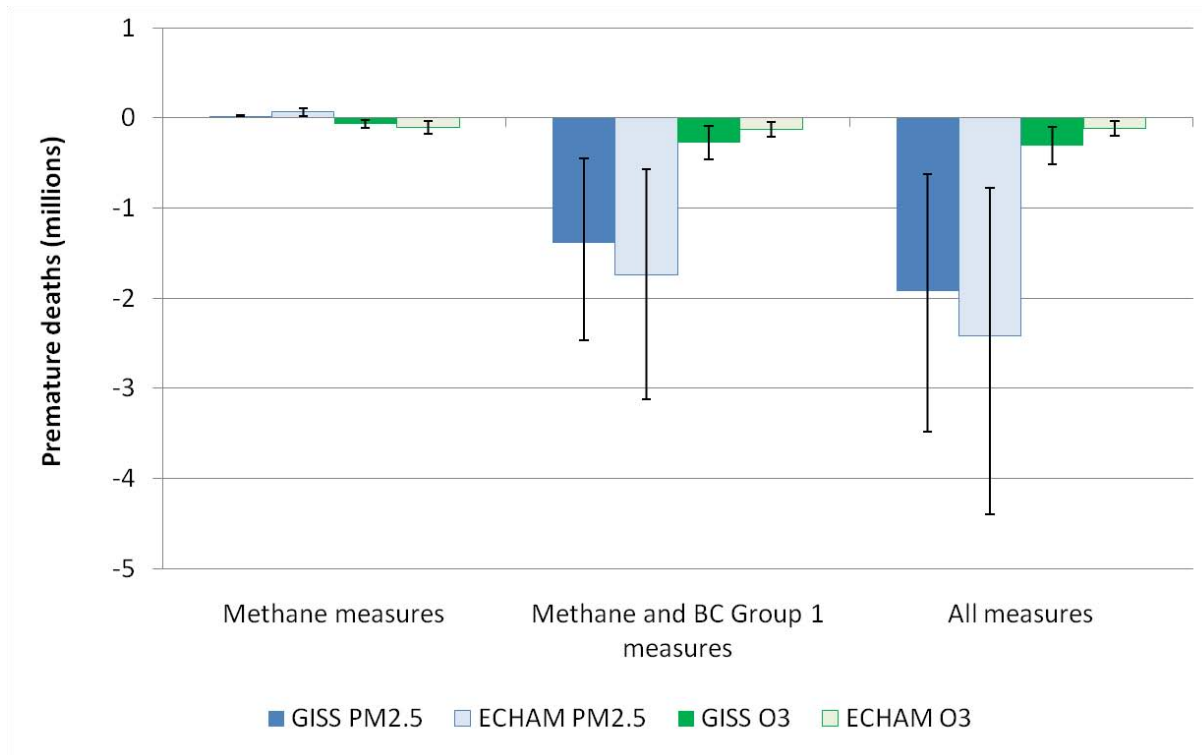
Supplemental Material, Figure 4. Change in estimated annual premature PM_{2.5} cardiopulmonary and lung cancer and ozone respiratory deaths (lives per 1000 km²) for the 2030 reference scenario relative to 2005, based on 2030 population.



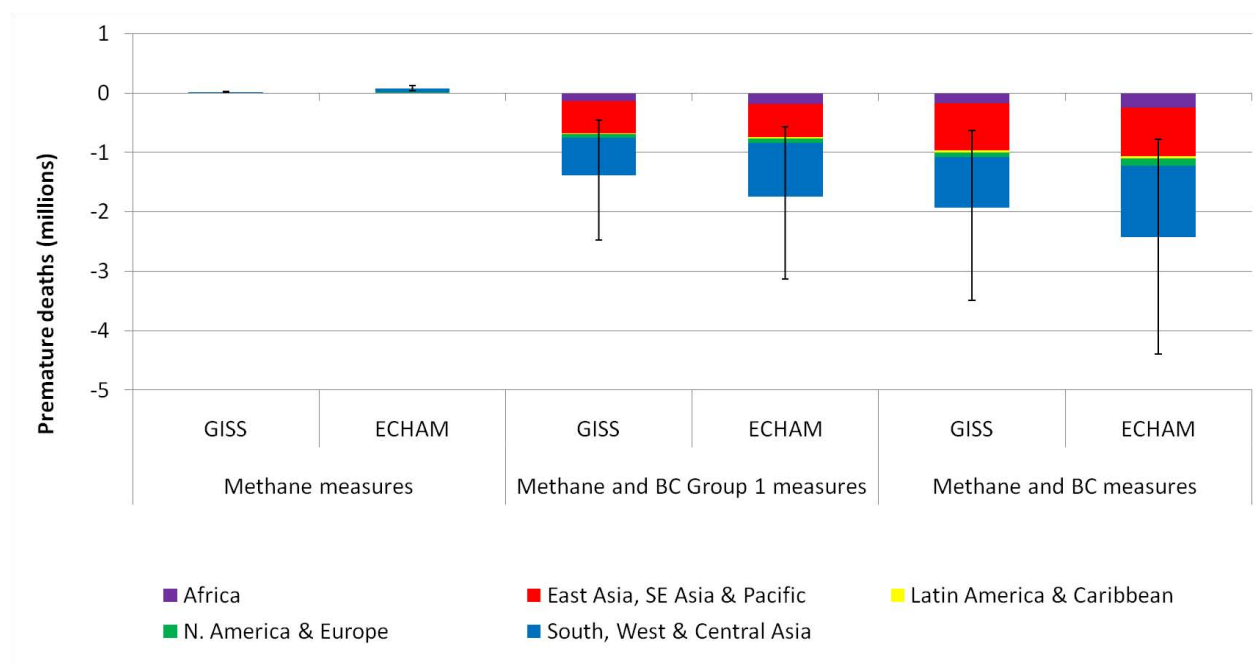
Supplemental Material, Figure 5. Regional change in estimated annual PM_{2.5} cardiopulmonary and lung cancer and ozone respiratory mortality for the 2030 reference scenario relative to 2005, based on 2030 population. Confidence intervals (95%) reflect uncertainty in the CRF only.



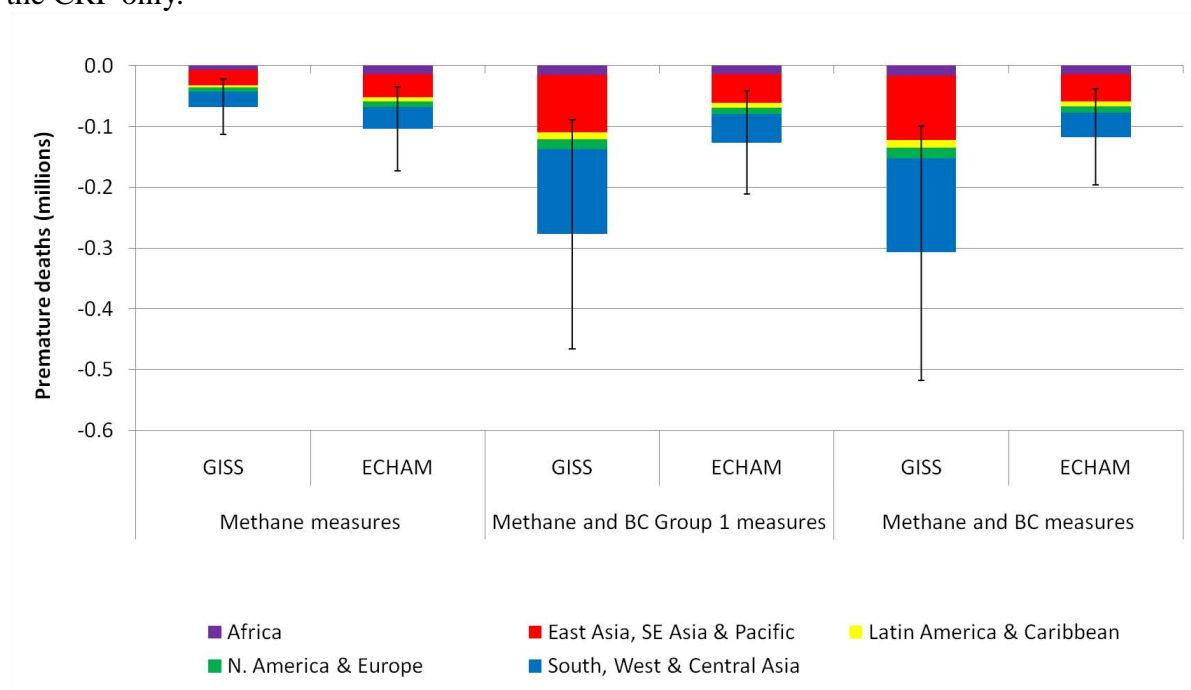
Supplemental Material, Figure 6. Change in estimated annual premature PM_{2.5} cardiopulmonary and lung cancer and ozone respiratory deaths (lives per 1000 km²) for the successive implementation of methane measures, methane plus BC Group 1 measures, and methane plus BC Group 1 and BC Group 2 measures, relative to the 2030 reference scenario, based on 2030 population.



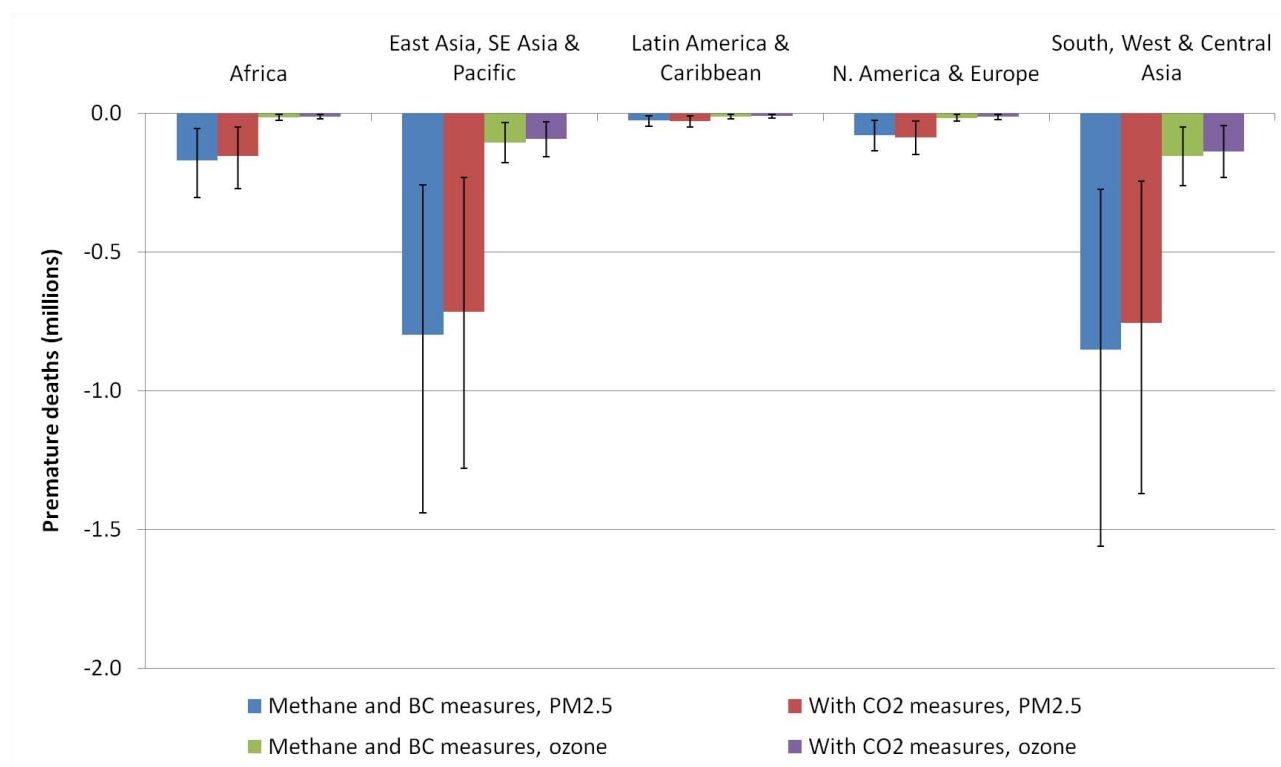
Supplemental Material, Figure 7. Estimated global annual avoided premature PM_{2.5} cardiopulmonary and lung cancer and ozone respiratory deaths for the successive implementation of methane measures, methane plus BC Group 1 measures, and methane plus BC Group 1 and BC Group 2 measures, relative to the 2030 reference scenario, based on 2030 population. Confidence intervals (95%) reflect uncertainty in the CRF only.



Supplemental Material, Figure 8. Regional change in estimated PM_{2.5} cardiopulmonary and lung cancer mortality for the successive implementation of methane measures, methane plus BC Group 1 measures, and methane plus BC Group 1 and BC Group 2 measures, relative to the 2030 reference scenario, based on 2030 population. Confidence intervals (95%) reflect uncertainty in the CRF only.



Supplemental Material, Figure 9. Regional change in estimated ozone respiratory mortality for the successive implementation of methane measures, methane plus BC Group 1 measures, and methane plus BC Group 1 and BC Group 2 measures, relative to the 2030 reference scenario, based on 2030 population. Confidence intervals (95%) reflect uncertainty in the CRF only.



Supplemental Material, Figure 10. Regional change in estimated PM_{2.5} cardiopulmonary and lung cancer and ozone respiratory mortality for the implementation of all methane and BC mitigation measures relative to the 2030 reference scenario and all methane and BC measures with CO₂ mitigation measures included in both the reference and mitigation scenarios, using concentrations simulated by the GISS model and 2030 population. Confidence intervals (95%) reflect uncertainty in the CRF only.

Comparison of results with previous studies

Here we compare results from this study with previous estimates of the health impacts of methane concentration reductions, black carbon emission reductions, and adoption of European vehicle emission standards in developing countries. West et al. (2006) calculated 17,000 avoided cardiopulmonary deaths in 2030 due to a 20% global methane reduction. This estimate is 10% lower than our ozone-mortality response to methane measures after adjusting for the difference in methane reductions (38% vs. 20%, assuming a linear relationship between emissions and concentration), a factor of 2 higher for long-term mortality vs. short-term mortality (Anenberg et al. 2011b), differences in population (9.16 billion vs. 8.4 billion), and a low-concentration threshold of 25 ppb used by West et al. (2006) that gave 2% lower results. Anenberg et al. (2011a) calculated that halving anthropogenic BC and OC globally avoids 157,000 and 1.05 million premature deaths annually in 2002. Scaling these results by the larger emission changes in this study (69% and 79% for BC and OC) and population growth (30% higher in 2030), the adjusted estimate (BC+OC) is 4% higher than our PM_{2.5}-mortality response to all measures based on GISS simulations (40% higher using the same RR estimates from Krewski et al. 2009) and 20% lower than the ECHAM-based response. Adopting European vehicle emission standards in developing countries has been estimated to avoid 200,000 premature deaths annually in 2030 (Shindell et al. 2011), ~10% of the health benefits of all measures calculated here using the same GISS model (14% using the same GISS model and CRF from Krewski et al. 2009).

References

- Anenberg SC, Talgo K, Arunachalam S, Dolwick P, Jang C, West JJ. 2011a. Impacts of global, regional, and sectoral black carbon emission reductions on surface air quality and human mortality. *Atmos Chem Phys* 11:7253-7267.
- Anenberg SC, West JJ, Horowitz LW, Tong DQ. 2011b. The global burden of air pollution on mortality: Anenberg et al. respond. *Environ Health Perspect* 119:a158-a159.
- Bond TC, and Sun H. 2005. Can reducing black carbon emissions counteract global warming? *Environ Sci Technol* 39:5921-5926.
- Fuglestad JS, Shine KP, Bernsten T, Cook J, Lee DS, Stenke A, et al. 2009. Transport impacts on atmosphere and climate: metrics. *Atmos Environ* 44:4648-4677.
- International Energy Agency (IEA). 2009. *World Energy Outlook 2009*. Paris:International Energy Agency.
- Krewski D, Jerrett M, Burnett RT, Ma R, Hughes E, Shi Y, et al. 2009. *Extended Follow-up and Spatial Analysis of the American Cancer Society Study Linking Particulate Air Pollution and Mortality*. Boston, MA:Health Effects Institute.
- Lamarque J-F, Bond TC, Eyring V, Granier C, Heil A, Klimont Z, et al. 2010. Historical (1850-2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: Methodology and application. *Atmos Chem Phys* 10:7017-7039.
- Shindell D, Faluvegi G, Walsh M, Anenberg SC, Van Dingenen R, Muller Z, et al. 2011. Climate, health, agricultural and economic impacts of tighter vehicle-emission standards. *Nature Climate Change* 1:59-66.
- Shindell D, Kuylenstierna JCI, Vignati E, Van Dingenen R, Amann M, Klimont Z, et al. 2012. Simultaneously mitigating near-term climate change and improving human health and food security. *Science* 335:183-189.
- UNEP (United Nations Environment Programme). 2011. *Opportunities to limit near-term climate change: An integrated assessment of black carbon and tropospheric ozone and its precursors*. Nairobi:United Nations Environment Programme.
- West JJ, Fiore AM, Horowitz LW, Mauzerall DL. 2006. Global health benefits of mitigating ozone pollution with methane emission controls. *Proceedings of the National Academy of Sciences* 103:3988-3993.